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ORIGINAL ARTICLE

Robotic fiber placement process analysis and optimization using response surface method

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Abstract Unlike traditional materials, composites are carefully designed materials suitable for specific applications. Conventional methods of fabrication of composite structures have proven to be labor intensive and time-consuming. Robotic fiber placement is a composite fabrication technique that increases the flexibility of fiber placement process and allows for the fabrication of more complex structures. This study is aimed at analyzing and optimizing the robotic fiber placement process parameters. Many experiments have been conducted to analyze gas torch temperature, fiber laying head speed, and fiber compaction force and the process is optimized using response surface method.

Keywords Robotic fiber placement · Process parameters · Optimization

1 Motivation

Composite materials have gained popularity in products that need to be lightweight but strong enough to take harsh loading conditions. Fiber reinforced composites offer many advantages due to their attractive strength-to-weight and stiffness-to-weight ratios, which have made these materials quite suitable for aerospace and automotive applications. The traditional approaches of producing fiber reinforced composites involve manual hand lay-up, tape laying, and filament winding techniques; but all these methods are time-consuming, labor intensive, and generate high level of scrap material, whereas the current industrial requirements demand faster and more cost-effective processes [16]. The robotic fiber placement is a method that addresses these industrial requirements and provides not only flexibility and high throughput rate but also produces lesser scrap during production process. However, owing to a variety of materials used and the components produced, the process mechanism is not thoroughly investigated and the process parameters relationships with the quality and production rate must be established in order to overall improve the performance of the process.

This paper is organized in such a way that subsection 1.1 provides related work on the subject, subsection 1.2 gives the contribution of this study, whereas experimental setup developed and used in this study is given in section 2. The results of the experiments are reported in section 3, and the conclusion and future research directions are given in the section 4.

1.1 Related work

Fiber placement method has come a long way since its early development around 1980. From a few lab machines at different companies to fuselage production on different aircrafts, the technology is being used in a variety of applications with an array of material options. An overview of the materials, equipment, and applications is presented in [9]. Grant [5] provides a general review of automated processing methods currently being used to fabricate aircraft composite structures and presents a description of the automated tape layer process and the fiber placement process. This paper emphasizes the need for more variety of

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composites automation and more affordable machines in the aerospace composites industry. The limited variety of automation and the cost of equipment tend to limit the spread of automation throughout the aerospace composites industry. The development of a low-cost fiber placement machine is reported in [21] using industrial robot arms for motion control. This fiber placement machine is used to build composite panels with explicit curvilinear fiber architecture. A new method is introduced in [19] to place the task in the workspace and to define dimensional characteristics for the products. Shirinzadeh et al. [15] present the overall strategy for the establishment of a robotic fiber placement facility and describe the methodology for development of process planning and programming and simulation. In addition, the algorithm for automatic fiber path generation for open and closed surfaces is also discussed. Alici et al. [1] developed a lumped parameter model of a robotic fiber placement system consisting of a Motoman SK-120 robot, a force/torque sensor, a pneumatic actuator, and a stiff work piece holder. This study experimentally verified the purpose of predicting and characterizing the dynamic behavior of the fiber placement system. Shirinzadeh et al. [14] proposed a novel path planning algorithm for open-contoured structures, entitled the surface curve algorithm for robotic fiber placement. The algorithm aimed to produce a uniform lay-up of composite lamina, without gap and overlap between subsequent tows and a numerical investigation into the characteristics of the algorithm, was performed and presented. Schlimbach and Mitschang [13] introduced the method of the production cost estimation as a steady function based on the process-physics of the thermoplastic tape placement.

Tierney and Gillespie [20] presented a model for predicting through-thickness heat transfer and bond strength development based on intimate contact and healing at the ply interface. Experiments were carried out to validate these results for a wide variety of process conditions, and they showed that model-based predictive control could be used as a method for process optimization. The numerical results showed that bond strength development was significantly affected by the process set points (e.g., head velocity, heat input, and roller pressures), and that the resulting strength could vary significantly within the part based on the set points. Harper et al. [6] examined the effect of induced tow filamentization on preform loft, preform compaction, and laminate tensile properties for a directed fiber preforming process using random, discontinuous carbon fibers. Polini and Sorrentino [12] studied the influence of the main winding parameters on tension during the manufacturing of full section composite parts. The focus of the work was to determine both the geometric parameters characterizing the winding trajectory and the winding speed that allowed keeping the winding tension near the nominal value that had been planned to have good composite parts. The conclusions developed helped to understand the change in tension average value of winding typology. James and Black [8] developed a process window for filament winding and used thermal degradation data and a diffusion model to determine the upper and lower limits on process parameters. Pitchumani et al. [11] considered thermal degradation, void content, and dimensional change as product quality criteria to develop a process window for tape placement. Sonmez and Hahn [18] used the quality criteria for interlaminar bond strength, weight loss through thermal degradation, and crystallinity to find feasible sets of process parameters. Heider et al. [7] demonstrated the use of online optimization algorithms to calculate optimum process set points for automated thermoplastic tow-placement system based on artificial neural networks. The method presented modeling to predict material quality as a function of process set points that are computed by maximizing the throughput and maintaining a desired minimum quality. Sonmez and Akbulut [17] developed a process optimization scheme for tape placement. The goal of the study was to develop a process optimization scheme first to determine the set of process parameters that would result in a laminate with minimum peak residual tensile stress, and the second objective of the study was to apply the optimization scheme to achieve the highest possible lay-down speed. The numerical results showed that significant improvement could be achieved through optimization and a laminate with acceptable quality could be produced in situ.

1.2 Contribution

There are only a limited number of papers available that address analysis and optimization of automated thermoplastic placement systems. The work reported in Heider et al. [7] is aimed to maximize throughput while maintaining a minimum quality based on artificial neural networks; but in practical environments, quality must also be maximized along with the production rate. Furthermore, Heider et al. [7] considered only head velocity and the distance of the main torch as process parameters and did not take into account the torch temperature, which is also an important process parameter. Sonmez and Akbulut [17] developed an optimization scheme to achieve highest possible lay-down speed; thus, emphasizing only production rate without considering the quality of the product during optimization process. This study is aimed at analyzing and optimizing the process parameters of robotic fiber placement process. Three important process parameters, that is, gas torch temperature, fiber laying head speed, and fiber compaction force are analyzed and are optimized with the objective of maximizing both production rate and the quality of the product using response surface method. The merit of the approach is that further process parameters and responses can be added to the analysis and optimization scheme according to any specific requirement.

2 Robotic fiber placement experimentation setup

Compared with traditional fabrication techniques, robotic fiber placement offers many advantages including cutting and restarting of the fiber tows, debulking and consolidation of the material in situ, precise control of fiber placement angles and high degree of repeatability. Also, the use of robot manipulator increases the flexibility of the fiber placement process and allows for the fabrication of more complex structures [16]. Figure 1, taken from [16], shows the experimental robotic fiber placement system setup that has a six-degree of freedom robot manipulator with a creel system mounted on it. It is a vertically jointed-arm type Motoman SK 120 industrial robot with a minimum of 896 mm and a maximum of 2,573 mm space reachable. Its weight without all equipment required for fiber placement is 1,500 kg and its maximum allowable payload is 120 kg.

The system has a creel cabinet in which prepreg tows are stored that move through a series of tensioners and rollers before entering the fiber-processing head such that each prepreg follows an appropriate and aligned path to avoid entanglement of tows. Prepreg tows are fiber impregnated with a controlled amount of thermoplastic resin and then partially cured to give it tack quality. A fiber-processing head is attached to the end-effector of the robot. The measurement of compaction force during fabrication process is carried out by applying a force/torque sensor, installed between end-effector and the fiber-processing head, which is also used as a feedback device for fiber placement on contoured surfaces. Tows are cooled, at fiber-processing head, by a vortex cooling tube to reduce the tackiness of the tows, so that these do not stick to the guiding chute during the lay-up process. Then, tows are guided by rollers before heating and are compacted onto the substrate surface. The heat is applied to tows through a hot gas torch in order to increase tackiness such that tows can be bonded together. The hot gas torch uses nitrogen gas to heat the tows to prevent oxidative degradation during the bonding process. To remove trapped air and voids between the tows and the substrate material, a compaction roller applied direct force, and hence, the viscosity of the matrix resin is reduced and materials are bonded together, both by tacking and debulking the materials during the process. The residual stresses, voids, and warping can be prevented through proper compaction. The end-effector of the robot should be orientated during the fabrication process in such a way that the compaction roller pressure always remains normal to the substrate surface. Figure 2, taken from [16], shows the schematic diagram of the fiber placement assembly. The process is repeated till the desired thickness of composite material is achieved and then the component is vacuum bagged and has to be cured in an autoclave-processing oven to apply heat and pressure to the component for the process completion.

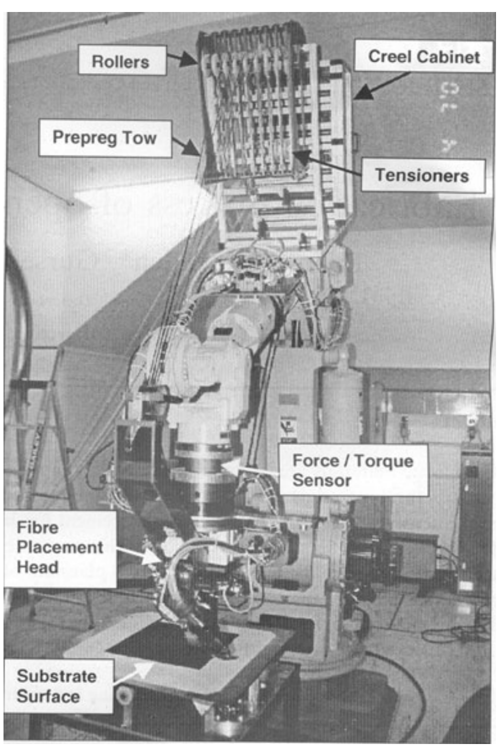


Fig. 1 Robotic fiber placement system setup

3 Experimental results and discussion

Many experiments have been carried out to manufacture flat panels with the objective to gain an understanding of the relationships of process parameters with regard to the

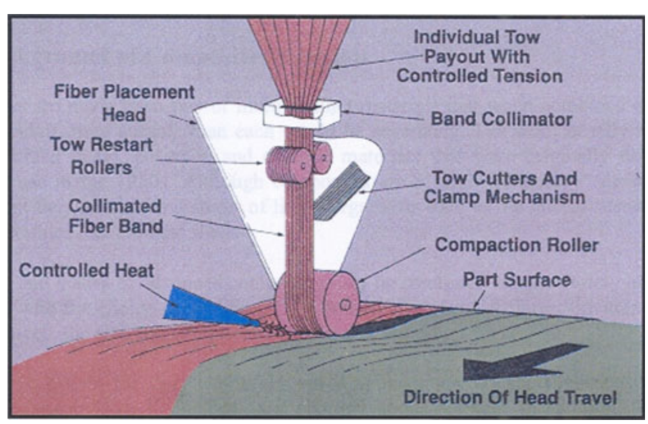


Fig. 2 Schematic diagram for fiber placement assembly

Fig. 3 The flat panel constructed through robotic fiber placement

quality of the panel and subsequently optimizing the process. The job program was compiled in C^{++} and was uploaded to the robot which was manipulated in the play mode. These experiments were performed with four layers of thermoplastic material placed at angles 0°, 45°, −45°, and 90° on the base material, carbon PPS tape. The flat panel, shown in Fig. 3, was constructed successfully after a number of brief stoppages due to the tows become too warm. The flat panel preform was of high quality, with minimal gaps between the tows.

During the placement process on any tool or surface of a workpiece, the tows are heated and compacted onto the substrate surface. A hot gas torch is used to apply sufficient heat to the tows to increase their tackiness such that they can be bonded together more readily. The hot gas torch uses nitrogen gas to heat the tows to prevent oxidative degradation during the bonding process. This is important since if the prepreg tows are not heated, they will not bond properly to the substrate and/or other layers/tows. Further, during the placement process, a compaction roller will apply direct force to remove trapped air or spatial gaps (voids) between the tows and the substrate material. In this way, the viscosity of the matrix resin is reduced and the materials are bonded together, both by tacking and debulking the materials during the process. Proper compaction is therefore necessary to prevent residual stresses, voids, and warping. Also, during the fiber placement process, the robot's end-effector must be orientated such that the compaction roller pressure always remains normal to the substrate surface. The robot velocity during the fiber placement process is also important as this determines not only the throughput of the system, but also affects the fiber placement quality of the finished composite component. During the fiber placement process, as the robot is moving, it is pulling the fibers through the pullies, tensioners, and guides, while simultaneously following the tool surface profile, which can be a complex contoured surface. Therefore, the robot speed affects how much heating of the prepreg fibers is carried out—i.e. the higher the speed, the higher the hot gas torch temperature is required in order to ensure the prepreg fibers are heated enough to be tacky to stick to the tool or previous layers. Furthermore, it must be noted that compaction process must be considered, especially on complex contoured surfaces. Hence the impact of three process parameters (input factors) is investigated during experimentation stage. These parameters include hot gas

Table 1 Experiment results

Process	Quality characteristic 1: first layer adhesion to surface					Quality characteristic 2: tows adhesion on subsequent layers				Quality characteristic 3: substrate remaining intact				Quality
	Parameters	$q11$	$q12$	$q13$	$q1$	$q21$	$q22$	$q23$	$q2$	$q31$	$q32$	$q33$	$q3$	Q
Temperature, °C	350	5	3	5	4.33	3	5	5	4.33	5	7	5	5.67	4.78
	400	7	5	5	5.67	5	5	7	5.67	5	7	5	5.67	5.67
	450	7	9	7	7.67	7	7	5	6.33	9	7	7	7.67	7.22
	500	7	5	7	6.33	7	7	7	7.00	7	9	7	7.67	7.00
	550	7	7	7	7.00	7	5	7	6.33	7	7	5	6.33	6.56
Head velocity, mm/s	10	9	7	7	7.67	9	7	9	8.33	7	7	9	7.67	7.89
	30	7	9	7	7.67	7	7	9	7.67	7	7	9	7.67	7.67
	50	7	7	9	7.67	7	9	7	7.67	7	7	5	6.33	7.22
	70	7	7	5	6.33	7	5	7	6.33	5	5	7	5.67	6.11
	90	7	5	7	6.33	5		5	5.67	5	5	7	5.67	5.89
Compaction force, N	100	5	5	7	5.67	5	7	7	6.33	7	7	5	6.33	6.11
	150	5	7	7	6.33	7	7	5	6.33	7	7	7	7.00	6.56
	200	7	9	7	7.67	7	7	5	6.33	9	7	7	7.67	7.22
	250	7	5	7	6.33	7	7	7	7.00	7	7	9	7.67	7.00
	300	7	7	7	7.00	7	5	7	6.33	7	7	5	6.33	6.56

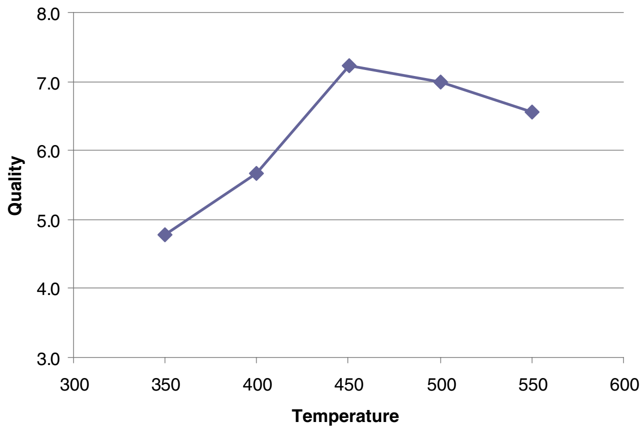


Fig. 4 Gas torch temperature and quality relationship

torch temperature, fiber-processing head speed and compaction force. The hot gas torch temperature is the temperature of the hot gas torch at the exit of the tows (fibers) and is measured in degree Celsius. The Robot head speed is the tow-placement feed rate measured in millimeters per second whereas the compaction force is the force at which the tows are placed/compacted onto the base material. The impact of these parameters is studied in relation to the quality level of the product which is defined in terms of three characteristics. These are adhesion of first layer of the thermoplastic material to the base surface, adhesion of tows on subsequent layers and substrate remaining intact. The first layer adhesion refers to the capability of the process in which the layer sticks to the tool surface (base material). Tows adhesion to the subsequent layers refers to subsequent layers sticking to the layers that have already been placed. Substrate remaining intact refers to the first layer remaining stuck to the tool surface; this is important as if the first layers do not remain on the tool surface, the following and subsequent layers cannot be placed on the top of the first layers. As the quality characteristics are qualitative in nature, these are coded on a quality scale varying from 1 to 9 in order to analyze the relationships between the process parameters and the quality level. Furthermore, it is advantageous to change quality characteristics to the coded quantitative form to optimize the process through response surface method subsequently. The following five point quality scale is used to code the quality characteristics:

1	3	5	7	9
Unacceptable	Fair	Good	Very good	Excellent

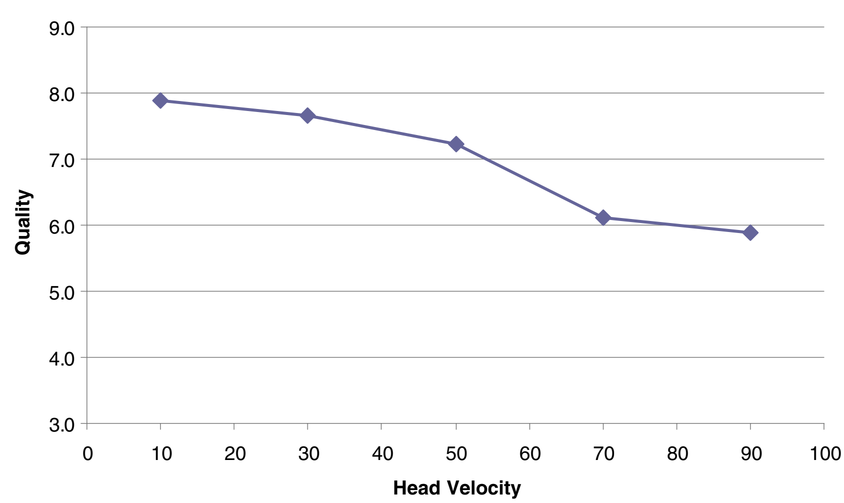
Each experiment is repeated three times and the products produced, for a specific experiment, are coded by the experiment staff according to the scale given above. Moreover, for each experiment, all three products are coded by three persons who codified the quality characteristics independently to ensure statistically unbiased data. The experiment results are shown in the following table (Table 1).

Where q_{IJ} refers to the Ith quality characteristic coded by the Jth experiment staff and q_1, q_2, q_3, and Q are the mean values such that:

$$q_1 = (q_{11} + q_{12} + q_{13})/3,\ q_2 = (q_{21} + q_{22} + q_{23})/3,$$
$$q_3 = (q_{31} + q_{32} + q_{33})/3,\ Q = (q_1 + q_2 + q_3)/3$$

The values of the process parameters are changed according to the provisions available in the experimental setup, and the five levels of process parameters variation are taken because such a setting is suitable for process optimization through response surface method, which is presented subsequently. Figure 4 shows the relationship between the gas torch temperature and the quality. The quality of the product is improving as the temperature is increasing because by increasing the temperature, the first layer adheres increasingly to the base material and similarly the subsequent fiber layers adhere together well. The substrate also remains intact as the temperature is increased. But the improvement of the

Fig. 5 Robot head velocity and quality relationship



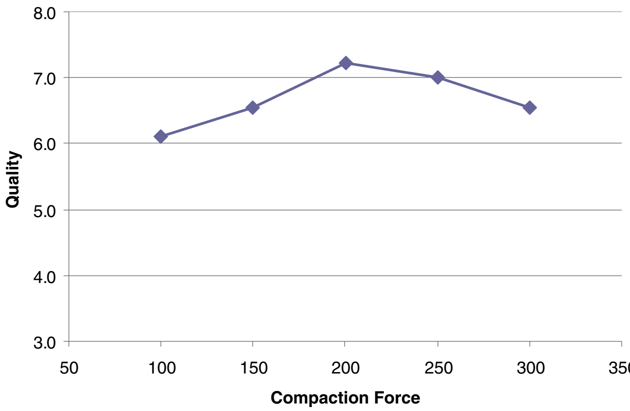


Fig. 6 Compaction force and quality relationship

quality as a result of an increase in temperature is observed up to a certain temperature limit, beyond which, a further increase in temperature causes thermal degradation resulting from excessively high temperature and hence, the quality is deteriorated. Figure 5 shows the robot head speed and the quality relationship. As the robot head speed is increased, the quality is deteriorated because fiber placement process requires a certain amount of time for its completion and a greater head speed means lesser process time is available. On the other hand, a high speed of the robotic fiber head is necessary in order to improve the production rate. This issue is further discussed when the process is optimized. The quality is also improving with an increase in fiber compaction force as is shown in Fig. 6, but the increase in quality is only significant up to certain level beyond, which no significant impact is observed. Furthermore, the compaction force is less significant regarding change in quality level compared with gas torch temperature.

The preceding analysis of the robotic fiber placement is based on one-factor-at-a-time approach as only one process parameter is varied at a time while the rest of two parameters are fixed at their respective middle levels. Nevertheless, more than one factor can be varied at a time in any experimentation process and is usually required in practical environments. This demands searching for a combination of process parameters capable of producing the highest quality product at the fastest production rate; a strategy referred here as process optimization that can be carried out through design of experiment, which is a planned approach for determining cause and effect relationships [10] and is a family of techniques for studying more than one process parameter in a single experiment [3]. Derringer and Suich [4] described a multiple response method, which makes use of an objective function, called the desirability function that works well for both single and multiple responses of an experiment. The general approach is to first convert each response, yi, into an individual desirability function di that varies over the range, $0 \le di \le 1$, where if the response is at the goal or target, then $di=1$, and if the response is outside an acceptable region, then $di=0$. The simultaneous objective function is a geometric mean of all transformed responses and is given by:

$$D = (d_1 \times d_2 \times \ldots \times d_n)^{\frac{1}{n}} = \left(\prod_{i=1}^{n} d_i\right)^{\frac{1}{n}}$$

Where n is the number of responses. If any of the responses fall outside their desirability range, the overall function becomes zero. For simultaneous optimization, each process parameter and response must have a low value (lv) and a high value (hv) assigned to each goal, such that for the maximum goal:

$$di = 0 \quad \text{if} \quad yi < \mathrm{lv}$$

$$0 \le di \le 1 \quad \text{if} \quad lv \le yi \le hv$$

$$di = 1 \quad \text{if} \quad yi > hv$$

Table 2 Response surface design

Run number	Temperature	Speed	Compaction force	Quality	Run number	Temperature	Speed	Compaction force	Quality
1	350	10	100	3.5	11	550	90	100	5.9
2	450	50	200	7.8	12	350	90	100	1.7
3	450	50	200	8.3	13	450	50	200	8.54
4	450	50	100	5.3	14	450	50	300	6.9
5	550	10	300	3.41	15	450	50	200	8.1
6	550	90	300	2.9	16	450	50	200	8.05
7	550	50	200	7.2	17	450	50	200	8.5
8	350	90	300	2.1	18	550	10	100	2.14
9	450	90	200	6.4	19	350	10	300	2.3
10	350	50	200	5.1	20	450	10	100	4.1

Table 3 ANOVA for response surface quadratic model

Source	Sum of squares	Degrees of freedom	Mean square	F Value	p value Prob > F	
Model	107.73	9	11.97	16.21	<0.0001	Significant
A—Temperature	4.69	1	4.69	6.36	0.0303	
B—Speed	0.19	1	0.19	0.26	0.6244	
C—Compaction force	0.063	1	0.063	0.086	0.7756	
AB	3.45	1	3.45	4.67	0.0561	
AC	0.11	1	0.11	0.15	0.71	
BC	1.07	1	1.07	1.45	0.2568	
A^2	9.04	1	9.04	12.24	0.0057	
B^2	5.01	1	5.01	6.79	0.0263	
C^2	8.13	1	8.13	11.01	0.0078	
Residual	7.38	10	0.74			
Std. Dev.	0.86	R^2	0.9359			
Mean	5.41	Adjusted R^2	0.8781			
C.V.%	15.88	Adequate Precision	10.981			
PRESS	116.92					

and for the minimum goal:

$$di = 1 \quad \text{if} \quad yi < lv,$$

$$1 \geq di \geq 0 \quad \text{if} \quad lv \leq yi \leq hv$$

$$di = 0 \quad \text{if} \quad yi > hv$$

In desirability function, each process parameter (input factor) and response can also be assigned an importance relative to the other process parameters and responses. Importance (ri) varies from the least important to the most important. By assigning different importance to different responses, the objective function is given by:

$$D = \left(d_1^{r_1} \times d_2^{r_2} \times \ldots \times d_n^{r_n}\right) = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{\frac{1}{\sum r_i}}$$

The shape of desirability function also changes with the addition of weights function, which is used to emphasize upper or lower bounds. RSM modeling and analysis have been carried out by using Design Expert 7.0.2 tool in this study. Response surface study is conducted through the use of central composite design and the particular design used

Fig. 7 Normal plot of residuals

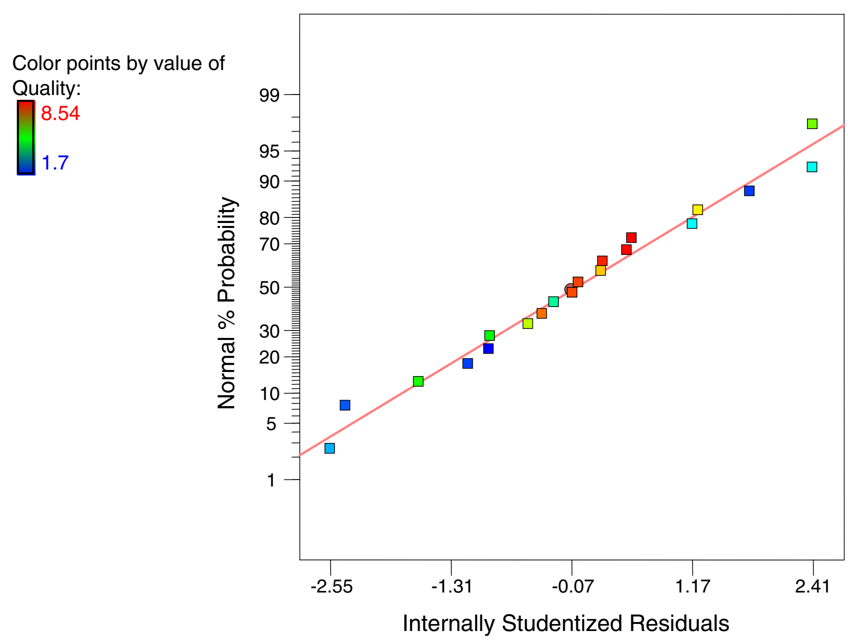
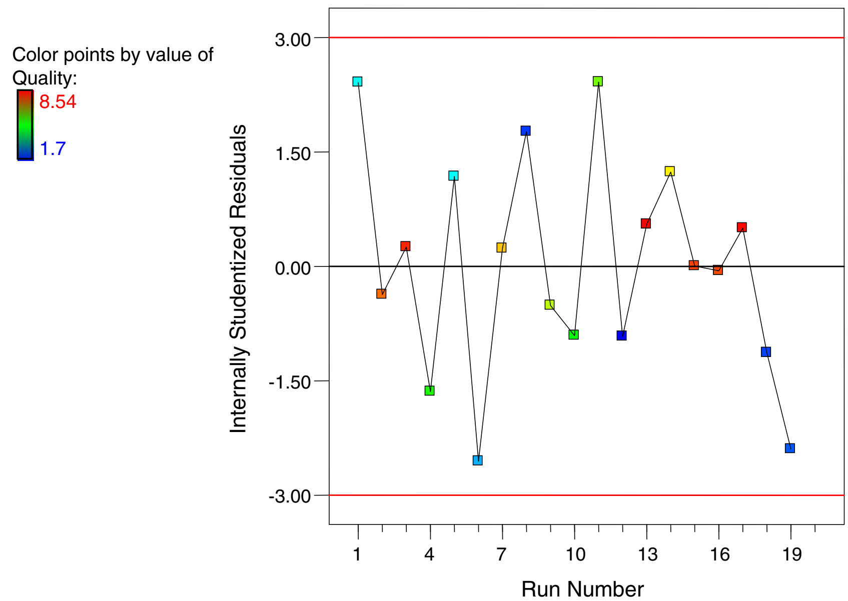


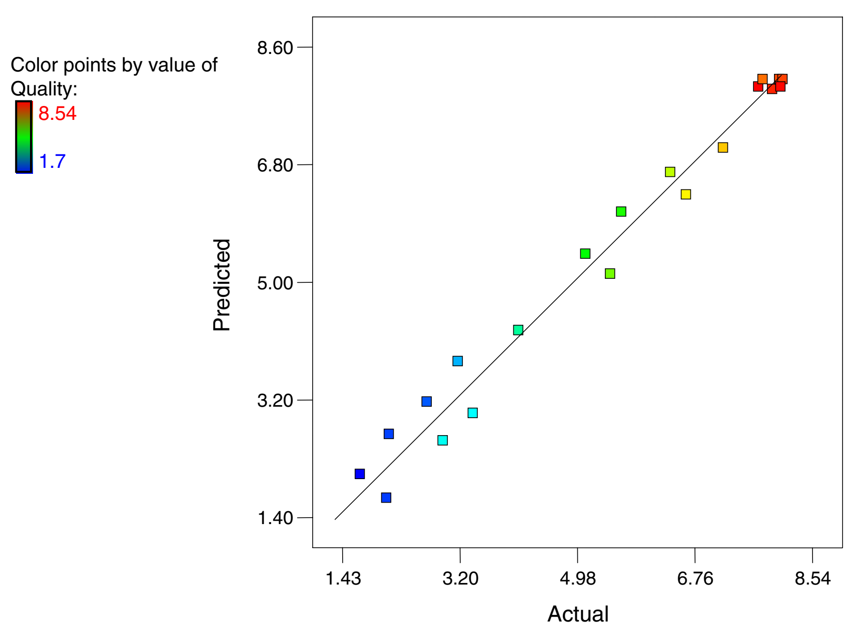
Fig. 8 Residual versus run plot



is face-centered central composite design for the approximation of the quadratic polynomial model. The following table (Table 2) shows the response surface design used in order to optimize the robotic fiber placement process that comprises of carrying out 20 independent experiments with different combination of process parameters determined through response surface method. Each experiment is repeated three times and the values of the quality have been coded as explained in the preceding experimentation stage of one-factor-at-a-time analysis. The response, that is quality, has been analyzed statistically to form the required polynomial. For validation purposes, the quadratic model has been tested for different statistical tests, which include analysis of variance (ANOVA), normal probability plot, residual versus run plot, and Box–Cox plot for power transformation. The following Table 3 gives the details of the ANOVA test.

The analysis of variance test shows that the quadratic model is significant. The adequate precision is a measure of signal to noise ratio, which should be greater than 4 in order to navigate the design space; thus a design, with the value of 10.981 is a valid design for optimizing the process. A detailed discussion on the terminology and concepts used in response surface method can be found in [2]. The normal

Fig. 9 Predicted versus actual plot



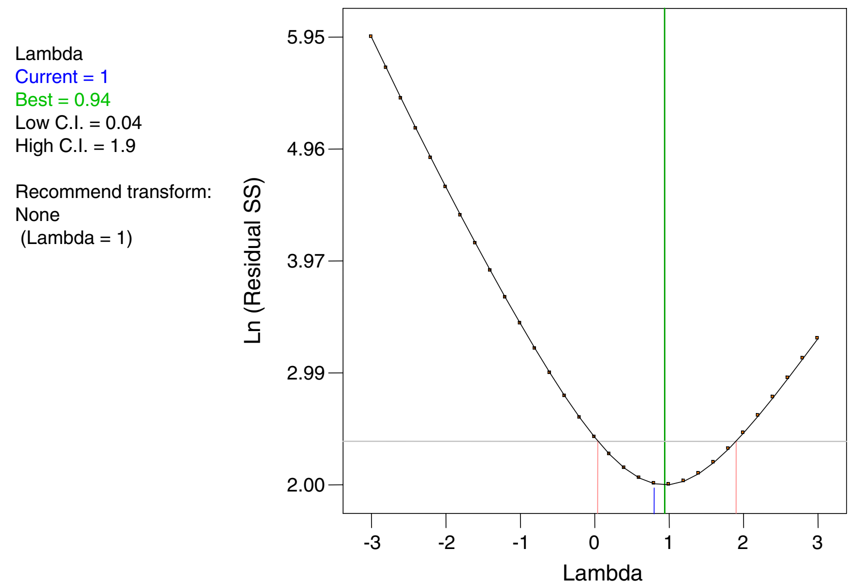


Fig. 10 Box–Cox plot for power transformation

probability plot indicates whether the residuals follow a normal distribution, in which case the points will follow a straight line. This plot is given in Fig. 7, which validates the model.

The residuals versus run is a plot of the residuals versus the experimental run order. It checks for lurking variables that may have influenced the response during the experiment. The plot should show a random scatter as trends in data indicate a time-related variable lurking in the background. The following residual versus run plot, given in Fig. 8, shows the points are scattered without forming any specific trend found in the data. Another important plot is "actual versus predicted plot," which shows actual response values versus predicted response values. This plot provides the information about the soundness of a model and helps to detect a value, or group of values, that is not easily predicted by the model and a straight line shows that the model is predicting the response correctly. This test is shown in Fig. 9.

The Box–Cox plot provides a guideline for selecting the correct power law transformation. The transformation of a response is recommended based on the best transformation power value found at the minimum point of the curve generated by the natural log of the sum of squares of residuals. The following figure shows the Box–Cox plot for the response surface study, which shows no transformation is required for the quadratic model of the quality (Fig. 10).

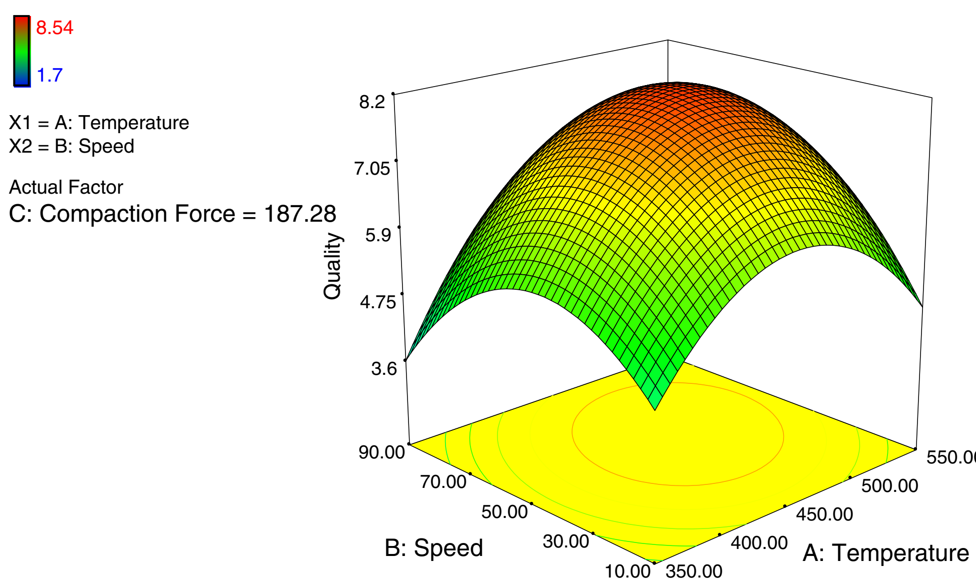
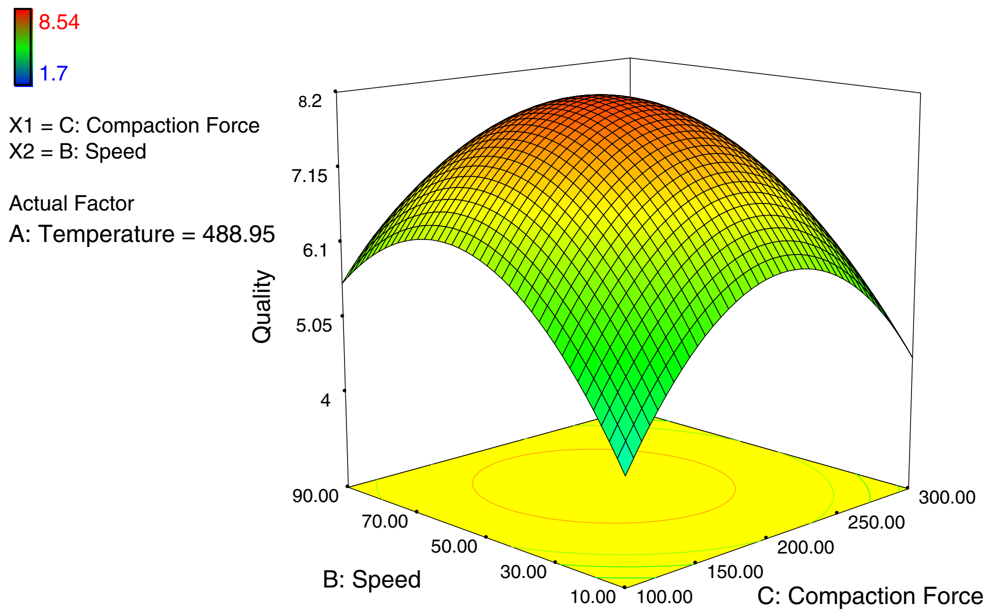


Fig. 11 Response surface of quality with process parameters, speed, and temperature, taken as base

Fig. 12 Response surface of quality taken compaction force and speed as base



All above tests validate the quadratic model which is given below. This model can be navigated in order to find the optimum values for both process parameters and the product quality.

$$\begin{aligned}\text{Quality} = & -38.22 + 0.16 \times \text{Temperature} + 0.05 \\ & \times \text{Speed} + 0.08 \times \text{Compaction Force} + 0.0001 \\ & \times \text{Temperature} \times \text{Speed} - 0.00001 \\ & \times \text{Temperature} \times \text{Compaction Force} \\ & - 0.000085 \times \text{Speed} \times \text{Compaction Force} \\ & - 0.0001 \times \text{Temperature}^2 - 0.0009 \times \text{Speed}^2 \\ & - 0.0001 \times \text{Compaction Force}^2\end{aligned}$$

The following are the response surfaces developed through the quadratic model "Quality." Figure 11 shows the response surface of quality with robotic fiber head speed and gas torch temperature as base parameters whereas Figs. 12 and 13 show the rest of two combinations of the base parameters.

The following tables (Tables 4 and 5) show the constraints employed and the optimum values of the robotic fiber placement process. The importance factor varies from 1 (the least important) to 5 (the most important). The gas torch temperature and the compaction force has been assigned the value of importance 3, which is the middle value between the least and the most important values, in order to navigate the whole design

Fig. 13 Response surface of quality taken temperature and compaction force as base factors

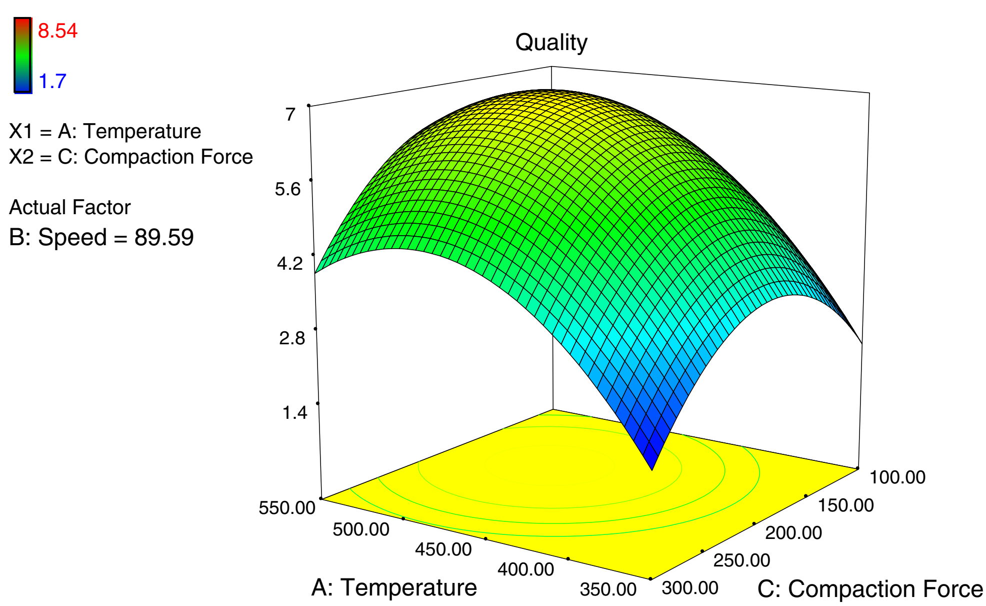


Table 4 Robotic fiber-process optimum values—process constraints

Name	Goal	Lower Limit	Upper Limit	Lower weight	Upper weight	Importance
Temperature	is in range	350	550	1	1	3
Temperature	is in range	350	550	1	1	3
Compaction	is in range	100	300	1	1	3
Quality	maximize	1.7	8.54	1	1	5

CI confidence interval

space without any specific preference. The robot fiber head speed is assigned the most important values, that is 5, in order to emphasize a higher speed, which ensures a high production rate. The quality is also assigned the most important response in order to achieve the best quality of the product. All these constraints can be modified according to specific requirements but every set of constraints will generate a distinct optimization solution. The values of lower and upper weight can also be modified to emphasize lower or upper bound of the desirability function. There is a range of these values from 0.1 to 10 in the design expert tool, whereas a value 1 means there is no emphasis on desirability function as far as weight values are concerned.

The constraint values show that both speed and quality are assigned the most importance, which is necessary to find higher quality along with a higher production rate. The process parameter optimum values show a very high value for the robot fiber head speed that has also forced the values of gas torch temperature and compaction force to a higher level compared with their initial values. The product quality is at a “very good” level (near quality scale point 7) that can be further improved if robot head speed is not assigned a very high importance but that will decrease the production rate of the process. The desirability value of 0.877 shows overall performance achievement keeping in view of all constraints which have been imposed.

The experimental results show that the quality of the product is improving as the temperature is increasing and the substrate also remains intact with an increase in temperature. But the improvement of the quality as a result of an increase in temperature is observed up to a certain temperature limit, beyond which, a further increase in temperature causes thermal degradation resulting from excessively high temperature, and hence, the quality is deteriorated. The quality is deteriorated as the robot head speed is increased because fiber placement process requires a certain amount of time for its completion and a greater head speed means that lesser process time is available. On the other hand, a high speed of the robotic fiber head is necessary in order to improve the production rate. The quality is also improving with an increase in fiber compaction force, but the increase in quality is only significant up to certain level beyond which no significant impact is observed. The second phase of experimentation presented in this paper is concerned with the performance maximization issue of the robotic fiber placement process using response surface method. The process performance can be improved according to constraints required. The important constraint in this study is to improve process throughput without compromising on the quality of the product.

4 Conclusion and future research

The robotic fiber placement is a manufacturing technique offering high potential for reduced manufacturing cost, low scrap rate during fabrication process, and improved product quality of complex composite structures. These advantages can be achieved through a careful examination of fiber placement process parameters in order to understand the relationships among different process parameters. The relationships among three process parameters, that is, gas torch temperature, fiber laying head speed, and compaction force, has been studied in this paper. This study has been extended to optimize the robotic fiber placement process with the objective of maximizing the product quality and production rate of the process. This study may be extended to include more

Table 5 Robotic fiber-process optimum values—optimum values for process parameters and quality

Temperature	Speed	Compaction force	Quality			Desirability
			Predicted value	95% CI low	95% CI high	
488.95	89.59	187.28	6.99154	5.55	8.43	0.877

CI confidence interval

process parameters and the analysis will be carried out for curved and cylindrical shapes of the product. Also, this study can be advanced through experimentation on different types of composite materials.

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